TIMING ASPECTS OF GPS-GALILEO INTEROPERABILITY: CHALLENGES AND SOLUTIONS

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Abstract

Interoperability with GPS has been one of the drivers for Galileo definition and design. This paper is dedicated to the timing aspects of the interoperability, related challenges, and solutions. Here, we discuss mainly technical issues; organizational and legal matters have been addressed by US-EU working groups and have been mentioned in the agreement on GPS Galileo cooperation signed by the US and EU sides on 26 June 2004.

The offset between GPS and Galileo system timescales (GGTO) will cause a bias between GPS and Galileo measurements in combined navigation equipment and, consequently, a bias in the user position & time solution. The first part of the paper reviews approaches to deal with this problem and presents simulations of positioning accuracy for users of the combined equipment.

The Galileo baseline foresees determination of GGTO on system level and its dissemination to users in the Galileo navigation message. The second part of the paper discusses the basic options for the GGTO determination (e.g., using a GPS time receiver connected to the physical realization of GST or a time transfer link between the Galileo Precise Time Facility and the US Naval Observatory). Finally, the accuracy of GGTO determination and prediction is studied with both simulated and real measurement data.

THE CHALLENGE OF INTEROPERABILITY

Since the 90s, the idea of a Global Navigation Satellite System (GNSS), a “system of systems” comprised of several individual satellite navigation systems, has been in the air. Originally, GNSS was understood mainly as GPS plus GLONASS and overlays like EGNOS. After GLONASS experienced constellation maintenance problems and GPS was left as the only player on the market, realization of the GNSS concept became somewhat distant. Now, GNSS is understood mainly as GPS plus Galileo (and, of

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14. ABSTRACT
Interoperability with GPS has been one of the drivers for Galileo definition and design. This paper is dedicated to the timing aspects of the interoperability, related challenges, and solutions. Here, we discuss mainly technical issues; organizational and legal matters have been addressed by US-EU working groups and have been mentioned in the agreement on GPS Galileo cooperation signed by the US and EU sides on 26 June 2004. The offset between GPS and Galileo system timescales (GGTO) will cause a bias between GPS and Galileo measurements in combined navigation equipment and, consequently, a bias in the user position & time solution. The first part of the paper reviews approaches to deal with this problem and presents simulations of positioning accuracy for users of the combined equipment. The Galileo baseline foresees determination of GGTO on system level and its dissemination to users in the Galileo navigation message. The second part of the paper discusses the basic options for the GGTO determination (e.g., using a GPS time receiver connected to the physical realization of GST or a time transfer link between the Galileo Precise Time Facility and the US Naval Observatory). Finally, the accuracy of GGTO determination and prediction is studied with both simulated and real measurement data.

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course, the overlay systems: WAAS, EGNOS, etc.). Being a virtual system of systems, GNSS will also offer virtual navigation services – combinations of signals and services of its individual components. These combined services are expected to have higher quality compared to stand-alone services of individual GNSS components.

However, the "plus" in the GNSS equation stands not for a "mechanical" sum. To enable combined services and their improved quality, GNSS components shall possess the feature called "interoperability." According to the IEEE definition, interoperability is "the ability of two or more systems or components to exchange information and to use the information that has been exchanged." In GNSS context, interoperability can be understood such that individual GNSS components should be designed, built, and operated in such a way that they do not "jam" each other and allow one to combine their signals in a navigation service of a superior quality. Obviously, the combination of signals occurs in the user receiver. Nevertheless, it is up to the systems to make this combination easy and efficient. Fulfillment of these conditions represents a challenge, which Galileo, as a newcomer on the market, has to meet. GPS has also to cope with it during its modernization.

Interoperability is a complex problem that has been extensively analyzed during Galileo definition studies (e.g., EU-funded projects GALILEI and GEM, ESA-funded GALA study). The following key interoperability aspects have been identified so far:

- signal structure and frequency selection,
- geodetic and time reference frames,
- constellation configuration,
- system policies and services guarantees.

In this paper, we concentrate on the timing aspects of GPS Galileo interoperability based on the results of Galileo C0 studies and following research. Here, we discuss technical problems and solution. The institutional and political aspects were treated by US-EU working groups; the major interoperability and cooperation issues are addressed in the US-EU agreement on GPS Galileo cooperation signed on 26 June 2004 in Shannon (Ireland).

GPS – GALILEO TIME OFFSET (GGTO)

Like GPS, Galileo will establish a system time scale, Galileo System Time (GST). The *de facto* characteristics of GPS Time and requirements to GST are summarized in Table 1.

GST, similar to GPS Time, will be steered to the international time scale TAI. Its estimated offset from TAI will be broadcast in the Galileo navigation message. The residual offset between GST and GPS Time can be expected to be about 57 ns (95%), considering today's performance of GPS Time and the required performance of Galileo. The offset between TAI representations derived from GPS and Galileo broadcast (UTC_{GPS} and UTC_{Gal} respectively) can be expected to be about 33 ns (95%). Here, we do not distinguish TAI from UTC, since these two time scales differ only by an integer number of seconds.

The GPS-Galileo time offset (GGTO) will represent an important issue for GPS-Galileo interoperability, since it will cause a bias between measurements in combined GPS/Galileo receivers.

To investigate the GGTO impact on user positioning accuracy, we assessed its potential characteristics in terms of Allan deviation (ADEV) (see Figure 1).

Table 1. GPS Time and GST.

Property	GPS Time	GST
Type of time scale	Composite Clock: average of GPS clocks computed in a Kalman filter	Master clock: steered active H-maser
Produced at	Computations performed at the Master Control Station	Physically produced at Galileo PTF
Access outside the system	Through broadcast corrections to satellite clocks	Through direct time transfer or through broadcast corrections to satellite clocks
Steering to TAI	Through USNO	Through Time Service Provider combining several UTC laboratories
Offset from TAI	14 ns (rms in 2004)	50 ns (95%, requirement)
Uncertainty of TAI offset	~ 9 ns (rms in 2004)	28 ns (95%, requirement)

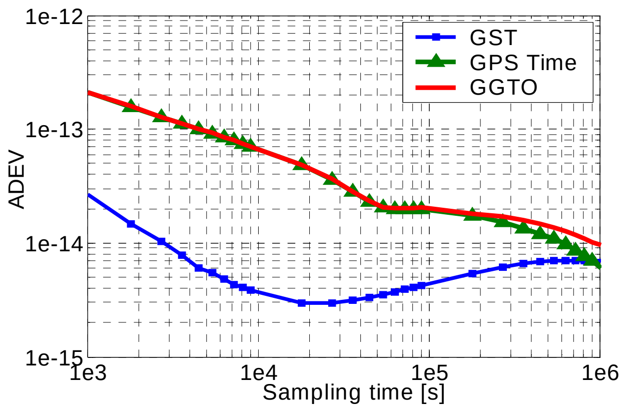

Figure 1. ADEV of GPS Time, GST, and GGTO.

When simulating GGTO, we used measured offsets between GPS Time and UTC (published by BIPM in the Circular T). The GST was "replaced" by a time scale that was considered to be representative for it (UTC (ORB)). Its offset from UTC was also extracted from the Circular T. The real data for GPS Time and UTC (ORB) were combined with simulated data produced with DLR's clock simulation tool. For details of GGTO simulations, refer to Reference **[1]**.

GGTO IMPACT ON POSITIONING ACCURACY

USER POSITIONING ALGORITHM

To study the impact of GGTO onto the user position accuracy, we assumed that users utilize the positioning algorithm described in the Minimum Operational Performance Requirements (MOPS) for GPS/WAAS Equipment (see **[2]**). This algorithm is based on a weighted least-mean squares technique.

To simplify the analysis, we employed a non-weighted version of it. The algorithm includes no assumptions on the dynamics of the user vehicle and its clock. The four unknown parameters are estimated only from the set of measurements available at a certain point of time.

The algorithm includes the following steps (see **[2]** for details):

- computation of residuals between modelled and measured pseudorange values. The modelled values are computed using an *a priori* (approximate) user position, satellite position, and clock offset available from the broadcast navigation message, and modelled propagation effects,
- computation of geometry matrix elements,
- computation of the least-mean square estimate of corrections to the original (approximate) user position and clock offset.

The least squares estimate $\hat{\mathbf{u}}$ of these corrections is given then by

$$\hat{\mathbf{u}} = \left(\mathbf{G}^{\mathrm{T}}\mathbf{G}\right)^{-1}\mathbf{G}^{\mathrm{T}}\mathbf{l} \qquad \text{Eq. 1}$$

Here, $\mathbf{l}$ is the vector of observation residuals, $\mathbf{G}$ is the so-called geometry matrix, and $\hat{\mathbf{u}}$ is the vector of estimated corrections to the *a priori* user position and clock offset. Vector $\hat{\mathbf{u}}$ includes three corrections to a 3D user position (typically, expressed in geodetic coordinates: latitude, longitude, and height) and one to the user clock offset (the clock offset is the difference between the user clock and the time scale of the navigation system).

However, with a combined GPS/Galileo receiver, the user has to cope with two clock offsets: one versus GPS Time and another one versus GST. This fact is not accounted for in the current MOPS algorithm and model of measurements. It will lead to a bias in the user positioning solution. The same will happen with the positioning solution of users who apply the broadcast GGTO correction: the bias will appear due to uncertainty of this correction, but will be reduced comparing to the solution without GGTO corrections.

Alternatively, the least-squares solution can be made for five unknowns: 3D position, user clock offset, and GGTO (or 3D position and two user clock offsets – versus GPS Time and versus GST). A similar approach has been used in combined GPS/GLONASS equipment. With the alternative algorithm, the basic processing scheme of the "classical" algorithm (residuals → geometry matrix → position & time solution) remains unchanged. However, the geometry matrix $\mathbf{G}$ will have five columns instead of four, and vector $\hat{\mathbf{u}}$ will consist of five elements. Obviously, other versions of an alternative algorithm can be proposed; the one addressed here is quite simple, but well-suited for service volume analyses.

To summarize the discussion above, GGTO will cause a bias in the user positioning solution. To avoid or reduce this bias, the user can either

- utilize the GGTO correction from the Galileo and/or GPS navigation message, or
- implement a navigation algorithm that solves for GGTO as an additional (the fifth) unknown.

SIMULATION SCENARIO

To estimate the impact of the broadcast GGTO uncertainty onto the user positioning accuracy with the standard four-unknown algorithm, a Monte-Carlo approach was utilized. The geometry of GPS and Galileo constellations was simulated over 72 hours for a regular grid of user locations Table 2 for

parameters of the simulation).

Table 2. Parameters of simulation scenario.

Property	**Value**
Galileo constellation	constellation of 27 satellites (Walker 27/3/9)
Galileo service	Open Service (dual-frequency)
GPS constellation	28 satellites as was available in April 2004
GPS Service	SPS dual-frequency (L1+L5)
User range error	1.05 m (Galileo) and 1.3 m (GPS)
Time span/time step	72 hours / 5 minutes
Grid resolution	3° (latitude) × 5° (longitude)
Uncertainty of broadcast GGTO	0, 5, 16 ns (95%)
User algorithm	MOPS (4 parameter) and alternative (5 parameter)

Further, the residual errors after correcting measurements with the broadcast GGTO value and with GPS and Galileo ranging errors for all visible satellites were simulated as a normally distributed random variable with a given standard deviation (2500 samples for each time step of the simulation). These errors were used to calculate the vector of observation residuals, $\mathbf{l}$. The least-mean squares algorithm (see Eq. 1) was employed to estimate horizontal and vertical positioning errors (both four- and five-parameter options were tested). Further, a 95% error percentile was estimated for each time step of the simulation. The procedure was repeated for each user location.

ACCURACY ANALYSIS

Table 3 summarizes results of the user positioning accuracy simulation for the scenarios described above in terms of global average and global worst-case 95% errors. The global average error is computed as an average over all simulated measurement epochs (3 days in 5-minute steps that correspond to 865 epochs) and all user locations. The worst-case error is the biggest error from all epochs and all user locations. The accuracy of Galileo-only positioning is also presented. Elevation cut-off angle was set to 10°.

Table 3. GGTO impact on user positioning accuracy.

	Average, 95%		**Worst, 95%**	
	HPE	**VPE**	**HPE**	**VPE**
Galileo only	2.1 m	3.7 m	3.3 m	6.6 m
GPS+Galileo, 5-parameter solution	1.6 m	2.8 m	2.8 m	5.4 m
GPS+Galileo, 4-parameter solution with broadcast GGTO				
95% GGTO - 0 ns - 5 ns - 16 ns	 1.5 m 1.6 m 1.7 m	 2.7 m 2.8 m 3.3 m	 2.8 m 2.8 m 4.1 m	 5.3 m 5.5 m 10.5 m

Also, we simulated the positioning accuracy for the open-sky condition with elevation cut-off of 30°. This cutoff is typically considered for simulations of urban visibility conditions. We obtained the worst-case HPE of about 60 m (95%) for solution with broadcast GGTO, and of 570 m (95%) for solution with five unknown parameters.

Here, we considered only the impact of different solution strategies onto the navigation accuracy. There will be also an impact onto the availability of solution: the availability of four-unknown solution is obviously better than one of the five-parameter solution.

ALTERNATIVE TREATMENT OF THE GGTO PROBLEM

There is a work-around for users of combined equipment who do not wish to use the broadcast GGTO, but still need to cope with restricted visibility conditions. Such users may just determine GGTO on their own from the five-parameter solution when enough satellites are available, and switch to the four-parameter solution utilizing the last computed GGTO value when satellite visibility conditions worsen. Such users would need a kind of smoothing algorithm to reduce the noise of computed GGTO estimates. Another source of GGTO determination error, the inherent GGTO variations of stochastic nature, would cause an additional error of about 0.2 ns (rms) after GGTO fixation for 15 min and about 0.35 ns (rms) after fixation of GGTO for one hour. That is equivalent to a change of the bias between GPS-Galileo measurements of 6 and 10 cm (rms) respectively. Such changes have negligible impact on the resulting user positioning error.

Summarizing the discussion on the GGTO impact on measurement and positioning accuracy, it is worth to remind ourselves that the cause of the impact is not the measurement itself, but the correction for satellite clock offset from the system time that is applied during the measurement processing. This correction – available from the broadcast navigation message – is referenced in GPS and Galileo to different time scales, to GPS Time and GST respectively. By referencing the correction to one common time scale, the problem of GGTO would be completely solved. Solving the problem on the system level – either utilization of GPS Time by Galileo or GST by GPS – seems to be unrealistic. However, the activities of IGS which computes GPS satellite clock correction referenced to its own time scale – IGS Time Scale **[3]** – are a step on the way to the common time for different navigation systems. In future, IGS might compute both GPS and Galileo clock parameters with respect to the IGS Time Scale eliminating GGTO-related problems for its users. Potentially, these products might be also available in real time, and their accuracy will be probably better than that of GPS and Galileo broadcast orbits and clock parameters. The IGS products might be made available to users either by broadcasting them in the navigation message of GPS and Galileo (as far as system operators are willing to offer this as an additional service), or via Internet comparable with the ESA's project SISNet. To explore these opportunities, additional consultations and coordination with IGS are needed.

GGTO DETERMINATION ACCURACY

GGTO DETERMINATION TECHNIQUES

As shown above, accuracy of the broadcast GGTO correction is an important GPS-Galileo interoperability issue. According to the present Galileo baseline, GGTO correction is to be determined with two techniques:

- Time transfer link between the PTF and USNO,
- Reception of Galileo Signal-in-Space (SIS) at the PTF.

The first technique is the primary one; the second technique will be implemented as redundant (secondary). A short description of both techniques follows.

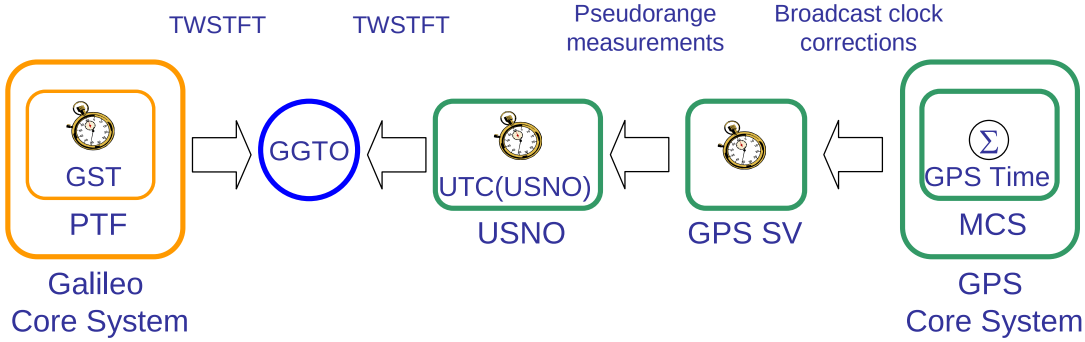

Figure 2. GGTO determination via link with USNO.

The USNO produces a real-time version of UTC, called UTC (USNO), and continuously monitors the offset of GPS Time with respect to it by receiving GPS SIS with timing receivers at USNO premises. From these data, daily values of the offset between UTC (USNO) and GPS Time are estimated. Thus, GGTO can be obtained by measuring the offset between GST and UTC (USNO) and correcting the

UTC (USNO)-GPS Time offset (see Figure 2). To implement this technique, a two-way time and frequency transfer link (TWSTFT) through a geostationary satellite is planned to be built between the Galileo PTF and USNO (the institutional issues of GGTO determination were recently addressed by a special US-EU working group; see, e.g., **[4]**).

Here, special attention to hardware calibration issues should be paid, since the accuracy of this link will be affected by two types of calibration uncertainties: (a) calibration error in TWSTFT link (typically, about 1 ns (rms)), (b) calibration errors in the GPS timing receiver(s) at USNO's premises (about 3 ns (rms)) **[5]**).

The secondary technique foresees determination of GGTO from reception of GPS SIS at the PTF by means of a GPS/Galileo time receiver (see Figure 3). However, the simplest approach would be to use a GPS time receiver connected to the GST physical realization available at the PTF (see Figure 4). The latter approach is discussed in the section on GGTO determination using GPS SIS. A study on the expected performance of the "combined receiver" method is presently ongoing.

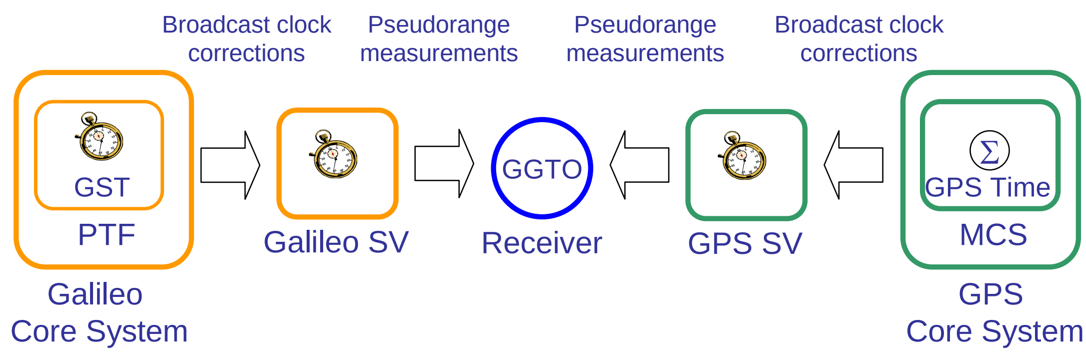

Figure 3. GGTO determination from reception of GPS and Galileo SIS.

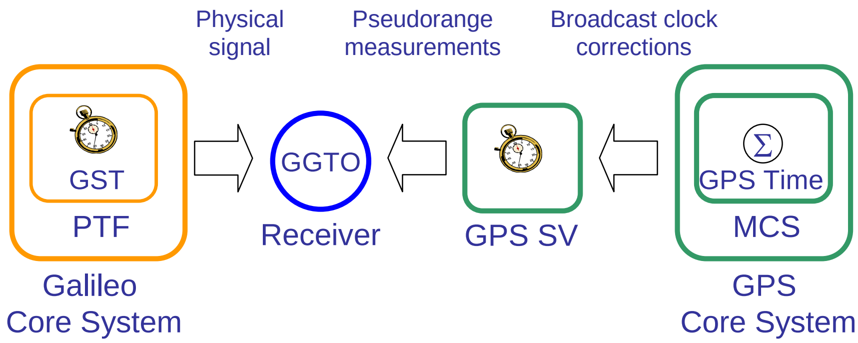

Figure 4. GGTO determination from reception of GPS SIS at PTF.

Also, for the secondary technique, calibration issues play a key role for the GGTO determination accuracy. It can be expected that the calibration uncertainty of a GPS time receiver at PTF will be of the same order of magnitude as for similar equipment installed at USNO's premises.

The current baseline foresees GGTO determination by both GPS and Galileo. The broadcast GGTO are also to be coordinated **[4]**. The organizational issues of such coordination are out of scope of this paper; however, it might be expected that it will be made through USNO, which would play for GPS the similar role in GGTO determination as it does in referencing GPS Time to TAI/UTC. Technically, GGTO determination results from the primary technique (link with USNO) will be directly available to USNO. GGTO estimates obtained with the secondary techniques (with a GPS or GPS/Galileo time receiver at PTF) should be provided to USNO in a dedicated transmission. It is not known to the authors whether additional GGTO determination techniques will be employed on the GPS side (e.g., using a Galileo or GPS/Galileo time receiver at USNO). In any case, Galileo will finally get at least three GGTO values (one from the primary and one from the secondary GGTO determination method, the third one from the GPS side). Then a common GGTO estimate should be computed and communicated to GPS. This problem should be additionally addressed in definition of Galileo algorithms and processing schedules.

GGTO Determination with a TWSTFT Link

A representative simulation of TWSTFT measurement errors is not straightforward, because their spectral characteristics are not yet well explored. Therefore, to obtain an idea on the accuracy of GGTO determination by means of the TWSTFT link between PTF and USNO, we employed real-world data. The role of PTF in our test was "given" to the Physikalisch-Technische Bundesanstalt (PTB) (see also **[6]**), which produces the national representation of UTC, called UTC (PTB), for Germany. The medium- and long-term performance of UTC (PTB) is considered to be similar to that of GST. Also, PTB operates a TWSTFT link with USNO. In the GGTO determination test, we used real [UTC (PTB) – UTC (USNO)] measurements and [UTC (USNO) – GPS Time] data from USNO. Combining these two types of data, we computed [UTC (PTB) – GPS Time] offset for the whole time span of the test (226 days between MJD 52700 and 52926). Due to an inherent rate of the original data, one offset value per day was obtained (see
Figure 5; the data gap is due to missing TWSTFT data). These data are considered to represent GGTO with a good degree of realism.

On the next step, we tested a GGTO prediction using two approaches:

- the GGTO value from the day before was used as the GGTO prediction for the day after;

- a line drawn through the GGTO values from two consecutive days was used to predict GGTO for the third day.

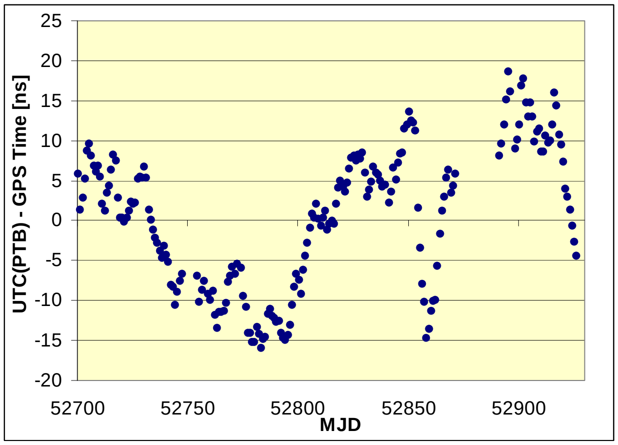

Figure 5. Offset between UTC (PTB) and GPS Time.

The obvious drawback of using real measurement data is the lack of true values of the measured quantity. Therefore, the prediction error was computed with respect to measurement data themselves. A histogram of prediction errors for the two techniques described above is shown in Figure 6.

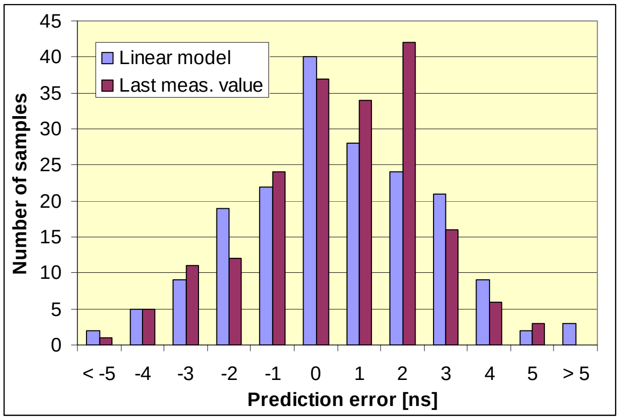

Figure 6. GGTO prediction error using link with USNO.

The results clearly demonstrate a superior performance of the prediction method using the last measured value (see Table 4; "outliers" mentioned in the table are prediction errors larger than 5 ns).

Table 4. Summary of GGTO prediction precision.

Prediction	RMS, ns	% of Outliers
Last value	2.05	0.5
Linear model	2.28	2.7

GGTO DETERMINATION USING GPS SIS

Simulations of GGTO determination from reception of GPS SIS at PTF were discussed in **[1]**. The best-case GGTO prediction error was estimated to be about 2.2 ns (rms). Also, prediction with the last measured value demonstrated better accuracy than prediction with a linear polynomial. Here, we study GGTO determination accuracy with real-world data. The GPS measurements here were collected at the Royal Observatory of Belgium (ORB) using a dual-frequency 12-channel GPS time receiver Z12T Metronome from 1 April to 30 September 2004. The reference time scale – UTC (ORB) – is produced from an active H-maser steered to UTC/TAI. Therefore, its performance is considered to be representative for GST. The measurement data (pseudoranges only) were processed using different types of satellite ephemeris and clock data. Also, two different techniques for calculation of tropospheric correction were employed (with a model with fixed zenith delay value and with a time-varying zenith delays calculated by IGS, in both cases the Hopfield mapping function was used). The processing scenarios are summarized in Table 5.

Table 5. Processing scenarios.

Scenario	SV Ephemeris	SV Clock Corrections	Trop. Correction
1	Broadcast	Broadcast	IGS
2	Broadcast	Broadcast	Model
3	Precise IGS	Broadcast	IGS
4	Rapid IGS	Broadcast	Model
5	Rapid IGS	Rapid IGS	Model
6	Ultra-rapid IGS	Broadcast	Model

In all scenarios, the pre-processed data were smoothed with a simple moving average (MA) filter. The data were split into daily intervals. The last value available from each of the days was used as the GGTO prediction for the next day. In all scenarios, the prediction error was computed against the common set of reference data obtained from processing of carrier-phase measurements collected at ORB by IGS. The statistics of resulting prediction errors are illustrated in Figure 7. From these results, it seems that

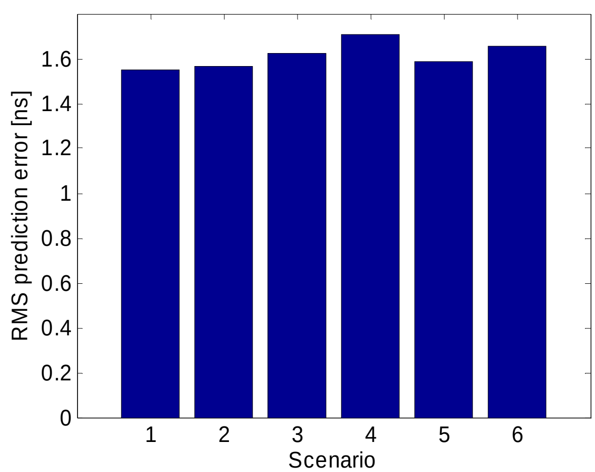

Figure 7. GGTO prediction error from reception of GPS SIS.

utilization of IGS products in processing of GPS data for GGTO determination purposes does not bring significant improvement of prediction accuracy. This is probably due to the fact that the noise component in measurement data is already well suppressed by the MA filtering, even when broadcast GPS ephemeris and clocks are used.

ERROR BUDGET FOR GGTO DETERMINATION METHODS

Above, we considered only the error of GGTO prediction. However, there is another important error source: calibration errors (biases in GGTO determination results). Tables 6 and 7 summarize the error budget for both GGTO determination methods that we considered in this paper (via link with USNO and from reception of GPS SIS at PTF).

In case a combined GPS/Galileo time receiver is used for the GGTO determination, a residual bias between GPS and Galileo measurements is expected to appear, because of the difference in propagation and reception time for GPS and Galileo signals, which have different types of coding. The magnitude of this bias could be of the order of nanoseconds.

Table 6. Error budget for GGTO prediction using link with USNO.

Uncertainty	**RMS, ns**
TWSTFT calibration	1
Calibration of cabling	1
Calibration of GPS time receiver at USNO	2-3
Prediction for 24 hours	2
Total	*3.2 – 3.9*

Table 7. Error budget for GGTO prediction using reception of GPS SIS at PTF.

Uncertainty	**RMS, ns**
Calibration of cabling	1
Calibration of GPS time receiver at PTF	2-3
Prediction for 24 hours	2.2
Total	*3.1 - 3.9*

Thus, no matter which GGTO determination technique is used, the results will be somewhat biased. To solve this problem, either the calibration accuracy needs to be increased or an additional calibration campaign with user receivers is needed. The campaign can be organized with several GPS/Galileo receivers installed at known locations and correcting their GPS and Galileo measurements with broadcast GGTO; the residual bias between GPS and Galileo measurements averaged over all receivers in the network will give an idea on the bias in the broadcast GGTO value.

The measurement bias represents, probably, the major problem for broadcast GGTO: it deteriorates not only the accuracy of GGTO determination by GPS and Galileo, but affects the end-user. Due to measurement biases (different propagation times for GPS and Galileo signals in the user's receiver), the user will have the "effective" GGTO as he observes it slightly differently than one determined at the

system level. In general, Table 6 and 7 should be extended by one row for user hardware bias that would further increase the effective uncertainty of broadcast GGTO correction.

CONCLUSIONS

Potential solutions of GTTO problem can be classified as follows:

- Solution solely on user level: GGTO is determined in the user receiver (five-parameter navigation solution). When satellite observation conditions are unfavorable, GGTO stays fixed following the results of recent solutions. In this scenario, there is no need in broadcast GGTO value.

- Solution solely on system level: GGTO is determined by GPS and Galileo and broadcast in the navigation message of both systems. Users utilize only the broadcast value without attempting to compute GGTO themselves. The user algorithm is the baseline four-parameter navigation solution.

- Mixed solution: As before, GGTO is determined by GPS and Galileo and broadcast in the navigation message. However, users utilize the broadcast GGTO value only if they do not have sufficient satellites to do that themselves. If enough satellites are available, GGTO is computed in the user receiver.

- Additional service solution: GPS and Galileo satellite clock parameters are computed with respect to a common time scale by some entity (Galileo itself, IGS or a commercial service provider) and made available to users either via Galileo (and GPS) broadcast or via other delivery channels like the Internet. Users do not utilize the "standard" clock correction from GPS and Galileo broadcast, but the ones referenced to the common time.

From the results of positioning error simulations that were presented here, one may conclude that

- under open-sky conditions with low elevation cutoff, the five-parameter solution performs well exhibiting only a slightly worse performance than the four-parameter solution obtained for zero GGTO. With a higher elevation cutoff, the worst-case error of five-parameter solution degrades quickly.

- the impact of the uncertainty of the broadcast GGTO correction on the user positioning accuracy is negligible, assuming that the Galileo baseline requirement (5 ns, 95% uncertainty) is kept.

- combination of Galileo with GPS for both cases (five-parameter solution or four-parameter solution with the broadcast GGTO correction) result in a better positioning accuracy than provided by Galileo alone.

Aside from the technical aspects, broadcasting of GGTO is an important psychological factor to enforce GPS-Galileo interoperability. Determination and broadcasting of GGTO by both GPS and Galileo are now included into the Galileo baseline and mentioned in the US-EU agreement on GPS-Galileo cooperation. However, to meet the Galileo baseline requirements to GGTO determination, hardware calibration issues should be carefully considered.

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QUESTIONS AND ANSWERS

ROBERT A. NELSON (Satellite Engineering Research Corporation): You identified an important problem as a common time reference between GPS and Galileo. Now, in the GPS, the time reference is a coordinate timescale in the Earth-centered rotating frame of reference. It is well known that relativity presents a number of very important corrections which are both secular and periodic.

I noticed in one of your slides where you are comparing a flow chart between going from spacecraft time and Galileo to GPS time and spacecraft time and GPS to GPS Time. I think you implied that there was a constant or secular bias, but I did not see you address the variable parts.

In the GPS, for example, for a particular satellite, there is a residual periodic correction which can be as much as 46 nanoseconds. So I am wondering to what extent you may have considered the effects of relativity and, in particular, the variable part of the correction.

JOHANN FURTHNER: This is not done, but maybe in future work, that we have consider these effects, and we can reduce these also. But it is clear that they are critical effects, so that we can get them down to 5 nanoseconds.